

Initial structural analysis of a Portuguese 'Muleta' lateen mainsail yard

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ABSTRACT: The 'Muleta' was a traditional Portuguese fishing boat. The last remaining example is the replica 'Álvaro Velho' whose 16.5 m wooden lateen mainsail yard failed. This paper concerns the ongoing work to design a composite material replacement. A simple bending only analysis design gave a 40% in weight reduction. To include the effects of shear, a finite element analysis approach has also been undertaken. A baseline numerical model of the strength and stiffness of the original replica yard (conservatively of Douglas Fir) has first been developed, and then very successfully corroborated with the previous simplified analytical model, giving confidence in both approaches. Development of the numerical model to consider shear effects and to give a new, refined composite materials design is underway. The aim is to facilitate economically viable and longer lifecycle composite yard replacements for both the Muleta and the numerous other traditional sailing craft of the Tejo.

Keywords: Traditional Sailing Vessels; Wooden Spars; Composite Materials, Finite Element Analysis (FEA).

1 INTRODUCTION

The 'Muleta' was a traditional fishing boat from the Tagus (Lisbon River, the Tejo) estuary, emblematic of the towns of Seixal and Barreiro and readily identifiable by its unique 'cloud of sails' and characteristically rounded bow (Figure 1).



Figure 1: A 'Muleta' (Laird Clowes, 1936)

The name 'Muleta' is not thought to come from the obvious literal English translation of 'crutch', but perhaps from the wooden stick used to extend a small red cape used in bullfighting, which together are reminiscent of the small sails extended along the bowsprit and long bumpkin at bow and stern, respectively. Another theory is that the origins are from the Latin 'motilus' in the sense of 'sluggish' describing the motion whilst fishing, as described below (Leitão et al., 2009).

In fact, the name 'Muleta' was also used generically for different types of craft using the same fishing method, such as the 'Botes da Tartaralha', and 'Batéis do Seixal', often referred to as 'Muletas Modernas'.

(‘modern’ as opposed to the ‘old’ round-bowed ‘Muletas Antigas’) (Carrasco and Peres, 1997) as shown in Figure 2 with a more traditional bow profile.

‘Tartaranha’ refers to the type of fishing method and net used by the Muletas (Figure 2), which is a form of pelagic (midwater) trawling performed with the boat ‘hove to’ and drifting slowly abeam (beware erroneous translations to ‘beam trawling’ which is not the case here) to leeward with the net extending to windward and pulled through the water via lines from both sides to the ends of the bowsprit and bumpkin (which are also visible in Figure 1).

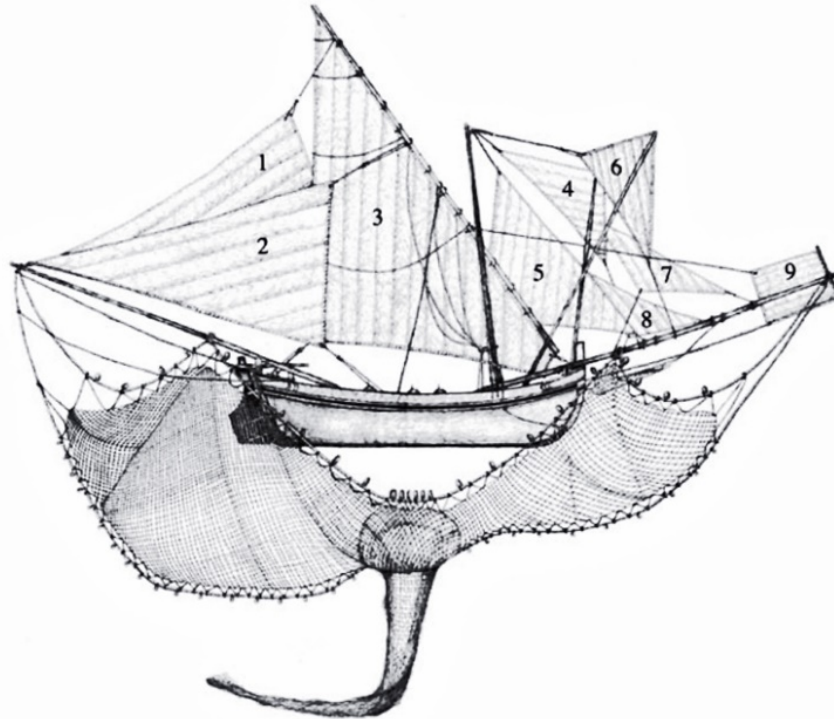


Figure 2: A ‘Modern’ Muleta or ‘Bote da Tartaranha’ (Curtinhal, 2007)

This fishing method explains the spectacular array of small sails extended fore and aft of the boat - they allow fine-tuning of the fore and aft position of the sail plan’s centre of effort whilst trawling, thus enabling control of the vessel’s sideways movement through the water against the variable currents acting on the large fishing net (as well as the windage and current forces acting on the vessel itself). Any sailor will immediately recognise that this would have still required an extremely expert level of seamanship. When sailing to and from the river mouth fishing grounds, however, only the lateen (also ‘bastardo’ in Portuguese) rigged mainsail was used, and the main yard supporting this mainsail is the subject of the present paper.

More on the fascinating history of these extraordinary boats may be found in (Baldaque da Silva, 1895; Gomes Pedrosa, 2016; Leitão et al., 2009) but sadly by 1901 there was only one working ‘Antiga’ Muleta and by 1928 no ‘Botes de Tartaranha’ of any form were left sailing (Câmara Municipal Barreiro, 2018).

However, in 2018 Jaime Ferreira da Costa & Irmão, Lda Construções e Reparações Navais constructed a replica Muleta (the ‘Velho Álvaro’) for the City of Barreiro. The design was based on the plans of the Portuguese Naval Museum (Museu de Marinha) and the amazing depth of information and plans in (Leitão et al., 2009), and mostly based on contemporary measurements, plans and drawings published in (Pâris, 1882) from those made by Raphael Monléon (curator of the Naval Museum of Madrid) and provided by Dr Fonseca Vaz (Portuguese Marine Minister) (Leitão et al., 2009).

This boat is run as a tourist vessel by Nosso Tejo Lda (Figure 3), and whilst sightseeing trips are only undertaken under motor, the wooden main yard failed and broke as the crew were moving the vessel under sail. The Authors were commissioned to design a replacement yard in fibre reinforced polymer (FRP) composites, as Dr Sutherland (with Dr Nuno Fonseca & Eng^o Mário Figueiredo) had previously done for the replica caravel Vera Cruz (Sutherland, 2023). The progress made to date is outlined in the present paper.

Table 1: Principle Dimensions of replica Muleta ‘Álvaro Velho’

Dimension	(m)
LOA (including rudder)	14.6 (15.4)
Beam	4.1
Depth (to cap rail)	1.7 (2.0)
Draft	0.8
Main Yard	16.5



Figure 3: The replica Muleta ‘Álvaro Velho’

2 DESIGN METHODOLOGY

In general, the same successful approach as used for the design of the 27 m long carbon yards for the Vera Cruz was applied here; since loading and geometry were both non-standard and variable (the yard is in bending around the mast, and is then free to rotate about all three axes), and since these craft ‘evolved’ in a ‘survival of the fittest’ sense over the years, the characteristics of the ‘original’ Vera Cruz replica wooden yards were used as a baseline. However, this was not as straightforward as it may seem; what do we mean by the ‘original’ yard with respect to the Muletas?

The ‘original’ wooden yard supplied with the ‘Álvaro Velho’ was hand-crafted to dimensions according to the passed-down experience of Mestre Jaime Costa (an at least fourth-generation master boat builder with over half a century of experience (Moreira, 2018)). Measurements of this (broken) wooden yard gave length and maximum diameter of 16.5 m and 187 mm (between 10 and 13 m from the tip, the ‘mast contact zone’), respectively - which are just 5% less than the diameters from the historical Museu de Marinha plans (which had to be scaled for length differences and since the yard was not dimensioned explicitly on the drawings calibrated measurements had to be used, and hence the diameters from the plans are themselves estimates). Hence the measurements taken from the ‘original’ replica wooden yard were assumed to be typical of a ‘historic’ Muleta yard.

However, unlike the historical wooden spars (which would have been fabricated from single pieces of timber since bonding using contemporary adhesives was not an option) the original replica wooden yard was shaped from spruce planks glued together using modern epoxy adhesives.

Further, would the original spars have been made from spruce, which became popular in the early part of the 19th century in yachting circles due to its lighter weight, but suffers from accelerated rotting? Eucalyptus, although available in Portugal from around 1860 (Cabral, 2019) and stiff and strong, is extremely heavy - plausibly too heavy to have been historically used. ‘Pinheiro-bravo’ (Maritime Pine), the native Portuguese pine species, seems to be the most likely to have been used historically.

Taking all these previous points into account, the design decision was made to use Douglas Fir as a conservatively stiff and strong pine species for the timber assumed, and the dimensions of the wooden replica spar as originally supplied by Jaime Costa when calculating the strength and stiffness behaviour of the baseline 'original' wooden yard. This design decision was thought to be appropriate even though this original (spruce) yard failed, understandably, at the mast (12 m from the tip), and, according to the crew, not under testing conditions.

Further investigations revealed that the yard had been stored unprotected for a number of years open to the hot Portuguese climate and hence environmental degradation became a prime suspect for this failure rather than under dimensioning of the spar. Also, although epoxy was used for joining the planks used together, finger joints within the planks made at the mill could not be assumed to be of such high performance resins and were hence easily degraded.

Additionally, the illustrations in Figures 22 and 23 of (Leitão et al., 2009) show very thick twisted traditional rope padding on both yard and mast at their intersection, yet Figure 3 indicates that only a thin layer of rope protection was used on the Álvaro Velho yard, and none on the mast. Further, on inspection of the numerous traditional craft in Seixal, the use of a single layer of neatly coiled modern synthetic braided rope (much 'harder' than traditional hemp twisted rope) was seen to be the norm. Further, impacts between yard and mast is now thought to be the main cause of the (repeated) failure of the original eucalyptus yards of the Vera Cruz. Finally, Figure 3 clearly shows the yard not hauled to the top of the Álvaro Velho's mast - as it is in Figures 22 and 23 of (Leitão et al., 2009) - but suspended from around 1 m of the halyard, allowing significant impacts between yard and mast, perhaps more so when sailing in lighter winds with any seaway running - the conditions when the yard broke. Hence, impact with the mast was thought to be another contributing, if not major, factor leading to the premature failure of the wooden replica Muleta yard.

Hence, the wooden replica yard, if not environmentally degraded, but well-padded and hauled right up to the hounds, would likely not have failed, and provides a suitable design baseline.

The Muleta is a smaller and far less stiff vessel than the Vera Cruz and the tip sections of the Muleta's yard significantly finer, meaning both that the maximum possible (in normal use at least) loadings will be lower and the ability to 'spill the wind' by twisting off of the head of the sail will be greater for the Muleta.

Also, it must be remembered that the use of the current vessel, that of tourist trips in light conditions at or above Lisbon, contrasts starkly with that of the original working boats that spent most of their time in the 'Mar da Muleta' ('Muleta Sea', the area between Capes Espichel and Roca) close to the edge of the continental shelf and open to the full force of the Atlantic Ocean, all year round, day in day out.

Hence, the new FRP design will be based on the strength and stiffness of a solid Douglas Fir yard with the dimensions of the original yard of the 'Álvaro Velho', an approach thought to be sufficiently conservative taking into account all of the points discussed above.

Previous experience with the 'Vera Cruz' (Sutherland, 2023) has shown that the use of FRP will both effectively eliminate rot and degradation (leading to a far longer lifecycle and hence significantly reduced environmental impact) and especially reduce weight. This latter point is of great advantage, both for the stabilising effect of less weight aloft, but also, very importantly for this tourist application (and as already confirmed for the youth sail training Vera Cruz), in the ease in which this enables the sail to be raised. This is acutely important for a tourist vessel where a short-handed crew is normal to maximise space for paying visitors, and the ability to raise the sails provides a clear advantage over the commercial competition.

Due to the ongoing (15 years) success of the 'Vera Cruz' FRP spars, the same simplified analytical design method is initially used here, as outlined in Section 3. However, since this method is known not to include the potentially significant shear stiffness and strength provided by the off axis plies, this will be refined via a Finite Element Analysis (FEA) to try to make the design less conservative (Section 4). This is thought to be justified due to the predicted light use and careful approach of the crew in such a small boat full of paying tourists.

Further, since the yard will be constructed (in-house with Eng. Mário Figueiredo), previous experience will be used to give a more 'designed for production' approach to reduce material and manufacturing costs - essential for the small company operating this historic vessel. One of the main differences from the Vera Cruz project is that to avoid the huge amount of costs associated with manufacturing bespoke moulds, the original (repaired) wooden yard will be used here as a mandrel (a cylindrical male mould).

In this paper, this ongoing work is detailed, including the simplified analytical design and the FEA model of the 'original' wooden spar to be used as a baseline for the composite spar design.

3 SIMPLIFIED ANALYTICAL DESIGN

The approach taken here is to ensure that the FRP yard is as stiff and at least as strong as the original wooden yard at metre-spaced ‘stations’ along the length of the spar assuming classical beam theory (Gere and Timoshenko, 1991). These calculations and the final results (after the five design cycles which were needed to obtain the required behaviour) are only outlined below in the limited space available here.

‘Stiffness’ is evaluated as beam Flexural Rigidity, EI , where E is the Young’s Modulus and I the local cross-section second moment of area. ‘Strength’ is evaluated as the bending moment to rupture:

$$M_r = \frac{I \sigma_r}{c} \quad (1)$$

where, σ_r is the failure strength and c the (maximum for minimum M_r) distance between the outer surface of the circular beam and the neutral axis (in this case the maximum radius, r).

Second moments of area for these circular sections were calculated using:

$$I = \frac{\pi r^4}{4} \quad (2)$$

The original wooden yard was of length 16.5 m and maximum diameter 187 mm. The measurements taken are compared with those from the Museu de Marinha Muleta plans and measurements of the mizzen yard of the Vera Cruz caravel in Figure 4.

Spruce (lighter) and also Douglas Fir (stiffer and stronger) material properties were used to give relevant bounds for the wooden spar behaviour as shown in Table 2.

Table 2: Wood material properties. ¹(Swedish Forest Industries Federation, 2023) ²(Ross, 2010)

	σ_r (MN/m ²)	E (MN/m ²)
Spruce ¹	75	11000
Douglas Fir ²	85	13400

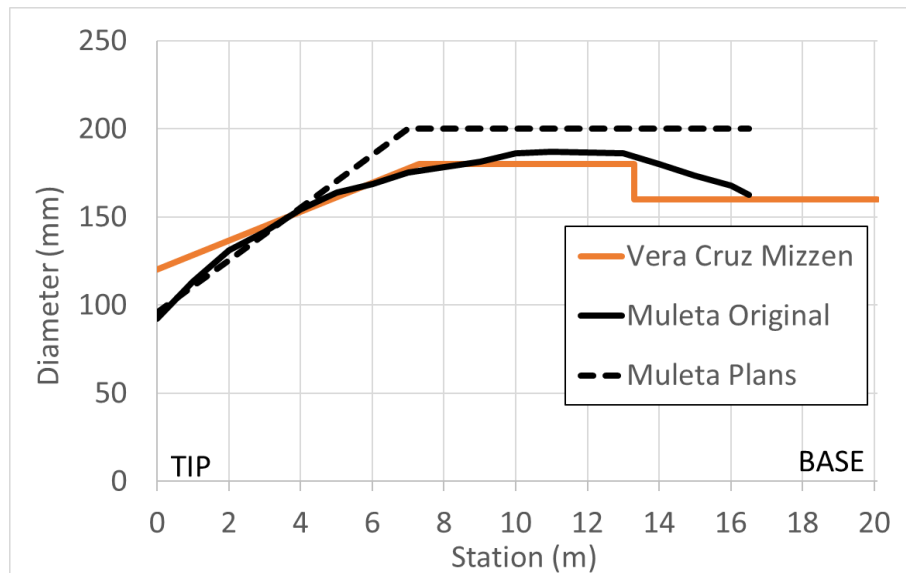


Figure 4: Yard dimensions

The calculated wooden yard bending stiffness and strength behaviours are presented in Figure 5 and Figure 6, respectively, but first, however, a necessarily brief outline of the design of the composite yard is described below.

Throughout the raw materials selection process the local availability of specific materials was often a deciding factor. Since the original yard will be used as a mandrel the dimensions of the composite yard are fixed. To reduce weight as far as possible, carbon fibre was selected as the main structural fibre reinforcement, which makes the choice of Epoxy resin as the matrix an obvious one to ensure the benefits of the carbon are not compromised. As a suitable cost to properties solution and facilitating layup of the fibres around the yard, 200 g/m² unidirectional (UD) standard modulus carbon was specified, and to save labour costs a 600 g/m² stitched multi-directional (0° /-45/ 90/+45) architecture was used where possible.

Since the yard will undoubtedly often hit against the mast and elsewhere, two outer, non-structural 300 g/m² plain weave E-glass fibre plies were incorporated to absorb impact damage and protect the brittle carbon fibres. A single interior glass ply (the first to be laminated against the male mould) gave a degree of ‘fairing’ to the hand-made wooden yard surface, avoiding ‘crimping’ of the following UD carbon plies.

Since the yard will be infused, Sicomin SR 8100 / SD 882X Epoxy Resin Infusion (low viscosity) System was used which is DNV-GL (TAK00001FU) and LR (MATS/4612/1) approved. Previous experience has shown that a Fibre Weight Fraction (FWF) of 0.7 is attainable, equating to Fibre Volume Fractions (FVF) of approximately 0.6 for the UD carbon and 0.5 for the woven glass plies; values which are ‘typical’. FVF is calculated from FWF via:

$$FVF = \frac{1}{\left[1 + \frac{\rho_f}{\rho_m} \left(\frac{1}{FWF}\right) - 1\right]} \quad (3)$$

where ρ_f and ρ_m are density of fibre and matrix, respectively (Shenoi et al., 1993).

Identifying the FVF values allowed selection of appropriate sources for the material property data required for calculations. Manufacturer’s data sheets generally provided some properties for suitable FVF example laminates, and missing values were taken from those of ‘AS4/3501-6 UD Carbon/Epoxy’ and ‘120/3501-6 Woven Glass / Epoxy’ from Tables A.4 & A.5 in (Daniel and Ishai, 2006) and from (USA Department of Defense, 2002, p. 2). FVF also allows calculation of the ply cured thickness, d , from:

$$d = \frac{A_w}{\rho_f FVF} \quad (4)$$

where A_w is the reinforcement areal weight (weight per unit area) (Shenoi et al., 1993).

The laminate stiffness and strength could now be calculated, and ‘The Laminator’ software (“The Laminator: Classical Analysis of Composite Laminates,” 2023) was used for this (Miller, 2006). In terms of the detailed design process this cannot be detailed here due to space restrictions and commercial sensitivities, but the main design constraints were taken from the previous experiences of the authors and GL ‘Design and Construction of Large Modern Yacht Rigs’ (Germanischer Lloyd, 2009):

- Use a well-balanced laminate
- Groupings of the same plies < 1.5 mm thick
- Avoid grouping 90° plies
- Compressive Young’s modulus E : Transverse > 20% Longitudinal
- In plane shear stiffness > 11% Longitudinal compressive Young’s modulus
- Avoid steps or bonded structures with significant different stiffness (peel stresses)
- Fibre-dominated (0°/±45°/90°) Layup recommended with minimum 10% in each direction
- Quasi-isotropic laminate in the zone around the mast contact.

The ‘base’ yard laminate was reinforced around the mast ‘zone’ to achieve a quasi-isotropic layup, with this extended to the yard base to minimise ‘pumping’ of the spar in a seaway and to keep the centre of gravity low for easier manhandling. The mast zone reinforcing laminate was tapered into the base laminate to avoid sudden stiffness changes.

Calculation of the laminate modulus and strength values enabled the same Classical Beam Theory approach as for the wooden spar to be carried out here, and compared with the latter results to complete an iterative design process. The results of this process are summarised in Figure 5 and Figure 6.

Figure 5 shows that the stiffness of the composite yard is at least as high as those of the wooden ones in its upper part, meaning that sailing characteristics should be agreeable. As designed, the lower part of the composite yard is much stiffer than those of the wooden ones, indicating better motions and manoeuvrability.

The different failure lines in Figure 6 deserve some explanation. Resin cracking, between 90° fibres, although to be avoided due to possible adverse effects on durability, does not indicate failure of the yard. The fact that this is never significantly lower than the spruce final failure values shows that this should not become a problem.

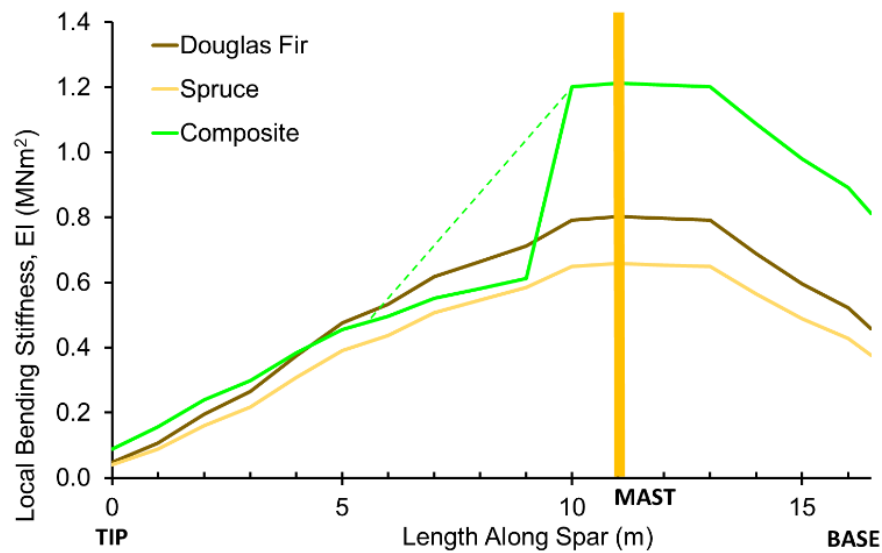


Figure 5: Muleta yard bending stiffness (dotted lines indicate tapering from mast zone to base laminate)

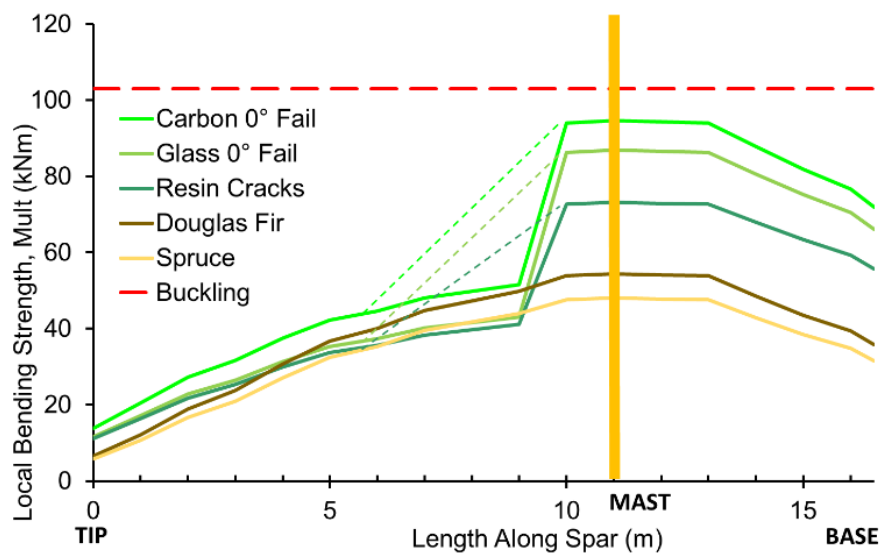


Figure 6: Muleta yard bending strength (dotted lines indicate tapering from mast zone to base laminate)

The first failure of 0° plies is the first ‘real’ failure, but this does not correspond to the final failure of the yard but just the very beginning of the progressive failure process as more and more fibres and plies fail – the yard will still have significant load bearing capacity in reserve.

Further, since the glass fibres are non-structural, their failure is not of concern, and in fact could be beneficial in identifying if the yard has been overstressed before catastrophic failure occurs (c.f. wooden spars, which crews are accustomed to, which ‘complain’ before they fail, allowing time to back off and/or carry out repairs).

Hence, the main failure of interest is that of the first 0° Carbon ply, which Figure 6 shows to be consistently stronger than even the Douglas fir yard in its upper part, and significantly higher than, almost double even, in its lower part and especially at the critical intersection with the mast – and it must be remembered that this is only the very first stages of failure, and so there is also an additional large ‘built-in’ Safety Factor. Also relevant is that the wooden yards already have a substantial built-in, ‘process of evolution’, safety factor to account for non-prescribed use and events, which are of course part and parcel of sailing.

The design also passes a conservative (i.e. not considering the internal bulkheads which will be included at the mast zone) check for buckling failure of a thin walled circular tube under transverse bending (Roark et al., 2002) as also indicated in Figure 6.

Finally, the weight of this composite solution yard is only around 60% of that of a wooden spar, and hence the design is considered to be sufficiently strong as well as having the desired stiffness profile.

However, this simple approach (whilst proving its effectiveness via 15 years of service for the Vera Cruz) does not consider shear effects and the laminates used incorporate a significant proportion of off-axis shear bearing fibres and is thus thought to be conservative. Hence, to quantify this effect and then to investigate whether or not lighter laminates could be used for a more refined design, an FEA of both wooden and composite designs has been undertaken.

4 FINITE ELEMENT ANALYSIS

FEA is a well-proven method for advanced analysis of marine structures (Miller, 2006). For this project the ANSYS software package was used to numerically model the Muleta's lateen spar. At the current stage of this study a solid model of the original wooden spar based on the dimensions in Figure 4 has been developed.

Given the slow response rate to loads, linear material properties and moderate deflections, a linear static analysis was performed with large deflection (membrane stress effects) included. As through-the-thickness shear stress results were desired for the failure analysis of the solid wood spars, solid elements were used. The solid models consisted of 39971 nodes and 24002 "Solid187" elements. This solid element is a higher-order pyramidal element with 10-nodes. It can model anisotropic, orthotropic or isotropic materials.

The first step in the FEA analyses was to check the basic approach and implementation against a simplified isotropic un-tapered (with average diameter of the actual tapered spar) closed-form solution for a fixed ended, 3-point beam bend loaded at the centre using a representative force. Nominal material properties (Aluminium 6061-T6) were used. The FEA predicted deflected shape was as expected, and the predicted deflections, stress results, volume and mass closely matched the closed-form solution (Roarke et al., 2002), giving confidence that the FEA model was correctly constructed.

As discussed in section 2, the wood species considered for design purposes here was Douglas Fir, whose properties are shown in Table 2 and were taken from (Ross, 2010).

Table 3: Material properties of Douglas Fir used in FEA

Property	Value (Ross, 2010)
Young's Modulus X, E_x	1.34×10^{10} (Pa)
Young's Modulus Y, E_y	9.11×10^8 (Pa)
Young's Modulus Z, E_z	6.70×10^8 (Pa)
Shear Modulus XY, G_{xy}	8.576×10^8 (Pa)
Shear Modulus YZ, G_{yz}	1.045×10^9 (Pa)
Shear Modulus XZ, G_{xz}	9.380×10^8 (Pa)
Poisson's ratio XY, ν_{xy}	0.292
Poisson's ratio YZ, ν_{yz}	0.390
Poisson's ratio XZ, ν_{xz}	0.449
Density	438 (kg/m ³)
Tensile Strength X, σ_{Tx}	1.08×10^8 (Pa)
Tensile Strength Y, σ_{Ty}	2.30×10^6 (Pa)
Tensile Strength Z, σ_{Tz}	2.30×10^6 (Pa)
Compressive Strength X, σ_{Cx}	4.99×10^8 (Pa)
Compressive Strength Y, σ_{Cy}	5.50×10^6 (Pa)
Compressive Strength Z, σ_{Cz}	5.50×10^6 (Pa)
Shear Strength XY, τ_{xy}	1.40×10^6 (Pa)
Shear Strength YZ, τ_{yz}	7.80×10^6 (Pa)
Shear Strength XZ, τ_{xz}	1.40×10^6 (Pa)

The boundary conditions applied in the FEA were based on observations from the yard rigged for sailing in photographs, e.g. Figure 3, drawings and plans, e.g. (Leitão et al., 2009), and measurements taken from the 'Velho Álvaro'. The yard has two main attachment points; at its base and at the mast.

For analysis purposes, here the yard is modelled horizontally, and x defined as along the yard (longitudinal), y as up and down and z as port and starboard (Figure 7). At the base of the yard (in Figure 3 shown for-

ward of the mast on the deck, but on the left in the following FEA analysis figures), two lines attached to the base are made fast to the deck to port and to starboard preventing translations in the y and z direction and rotation about the x-axis. This boundary condition is applied to a 2.5 cm band around the yard circumference at the base as the dimension of the existing notch in where these two lines attach (B in Figure 7).

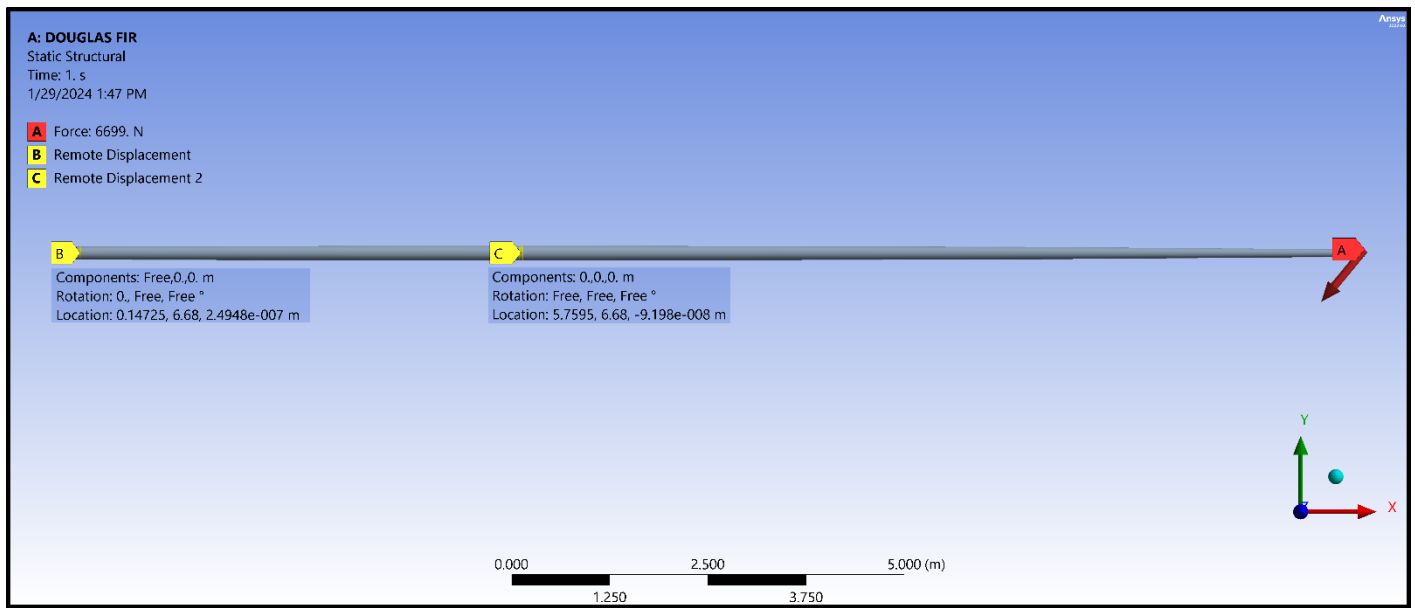


Figure 7: Wooden yard FEA boundary conditions and loading (6.7 kN)

It is assumed that the yard should be hauled right up to the mast by the halyard as in (Leitão et al., 2009) where it will hence be constrained in terms of displacements in all three axes, but will be free to rotate about all three planes (due to the elasticity of the halyard and especially of the protective rope padding between mast and yard). This mast attachment boundary condition is applied to a 5.08cm band around the whole yard circumference to simulate a typical diameter rope halyard wrapped around the spar (C in Figure 7).

The yard is loaded by the sail, but in a very complex manner where the sail lift and drag aerodynamic loads are transferred to the yard via membrane forces. The sheet at the sail clew, used to control the sail also gives a reaction force to these aero-dynamic forces, which are transferred to the yard. It is well beyond the scope of this study to try to evaluate the loading on the spar, so a worst case where all the load is applied to the tip of the yard via the sail from the sheet (measured to be at a 40-degree angle to the yard – to the horizontal in the FEA axis system) was used (A in Figure 7). This not only a conservative approach but also a valid one since the objective of this analysis is not to predict the actual breaking loads but to ensure that future composite material solutions are at least as stiff and strong as the original wooden yard. Also, since this was a comparison between analysis methods, for simplicity inertial effects were ignored.

The FEA model was then used to validate (or otherwise) the bending failure predicted by the simplified analytical method of section 3. Applying a nominal 1.0 kN force gave a stress of 13.9 MPa and a factor of safety (FOS) for the tensile stresses in the x-direction (longitudinally) of 7.72, at 5.83 m from the base, very close to the mast (at 5.76 m from the base). A further check was that the same stress was reported at the same distance from the base (but on the other side of the yard), but due to the much higher compressive strength of Douglas Fir, the corresponding FOS was 35.80. Although the large displacement analysis used leads to nonlinearities, a simple linear calculation was used to give a predicted loading of 7.72 kN for an $FOS_{tens,x}$ of 1. As expected this gave an FOS of close to but not equal to 1, and this value was then used to make another linear prediction of the failure load in longitudinal tension, and so on until this iterative approach converged.

The result of this FEA, for an $FOS_{tens,x}$ of 1.00, was 6.70 kN at 5.83 m from the base. Figure 8 (where tensile stress is defined as positive) shows that as expected, this longitudinal stress occurs on the upper surface of the yard and that the maximum compressive stress occurs on the lower surface at the same longitudinal position, close to the mast.

The simple analytical approach of section 3 resulted in a maximum ultimate bending moment at the mast of 54 kN.m which was constant for 1.5 m either side of the mast. Using this failure bending moment value and the (maximum) bending lever at the mast of a load applied at the yard tip (16.5 m from the base), and simple trigonometry to give the force required at the same 40° to the yard as in the FEA analysis resulted in a

failure load of 6.78 kN. This is a difference of little over 1% compared to the FEA result, thus delivering confidence in both FEA and the simple bending only analysis of section 3.

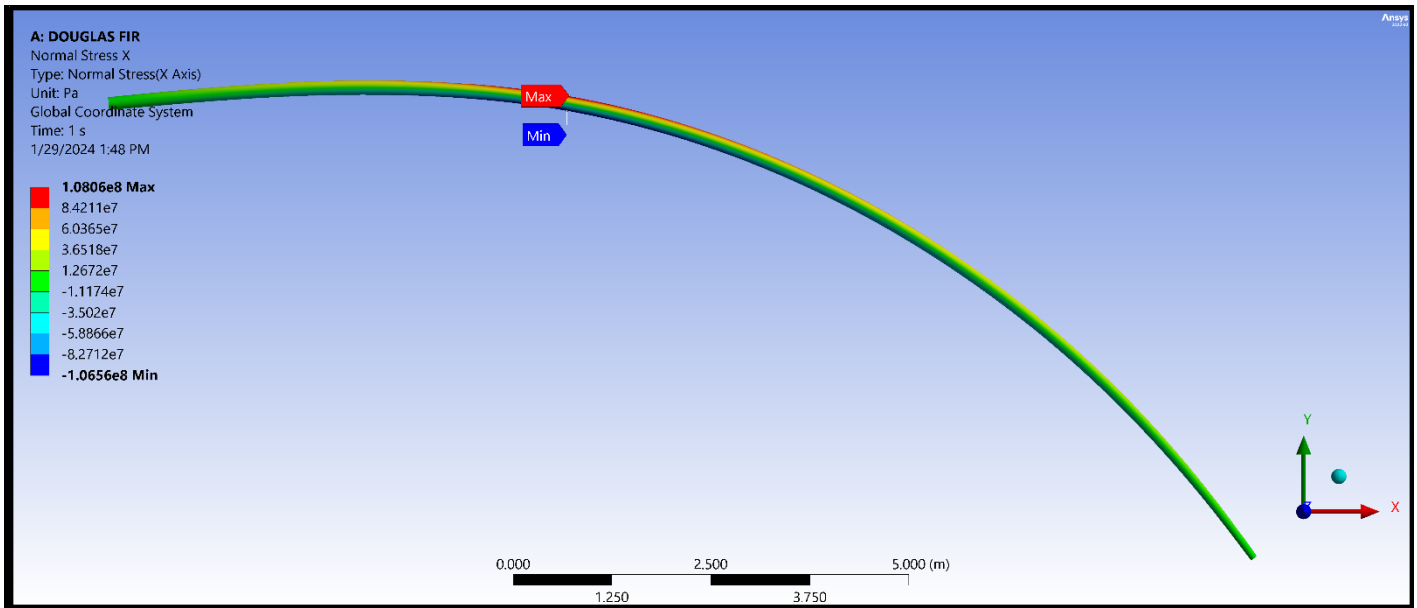


Figure 8: Wooden yard FEA real scale deflection and x-axis normal stress results at 6.7 kN

Figure 8 also shows the real deflected shape of the yard at bending failure, and the maximum deflection, at the tip, is 6.09 m. This appears to be a large deflection, but the deformed shape shown is certainly not excessive for a wooden spar.

However, so far the FEA model has only been used to predict the bending failure of the yard, but it was developed to investigate the possibility of shear and other effects on its behaviour. Now that the FE and simplified bending analyses have been corroborated, work is currently underway to include these aspects into the design.

5 CONCLUSIONS AND FURTHER WORK

A simple bending only analysis based design of a replacement lateen yard for a replica ‘Muleta’ traditional sail fishing boat has been completed. This design used the strength and stiffness of the original replica wooden yard as a baseline. In this, the conservative assumption of a Douglas Fir spar was also used alongside that of the actual Spruce of the wooden spar.

A design of a carbon and glass fibre reinforced epoxy composite material was then developed to give the same bending characteristics in the upper part (for good sailing characteristics) and increased strength (and hence stiffness) in the lower part, and especially at the mast where maximum bending moments occur, and the original wooden replica yard broke. This breakage was thought to be due to a combination of environmental degradation and / or unintended impact with the mast. This design resulted in a composite spar of just 60% the weight of the wooden one.

However, this simple analytical pure bending approach obviously does not consider the effects of shear, which are thought to be significant due to the off-axis fibre plies required for the composite solution.

Hence, a Finite Element analysis (FEA) has been undertaken to include shear, and other stresses, which again uses the original replica wooden yard as a baseline, but in this case only with the conservative assumption of Douglas Fir. This FEA has been corroborated with the simple analytical approach, giving a strength error between the two of just 1%.

Future work is underway to include the effects of shear and other stresses via FEA modelling of a composite material yard. This will then allow refinement of the current composite design, with the aim of facilitating economically viable replacement of the wooden Muleta yard, and providing a model for the numerous tourism traditional boats of the Tejo (Tagus) basin.

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